Lunar accretion from disks produced by non-canonical impacts

Julien Salmon[1], Robin M. Canup[1]

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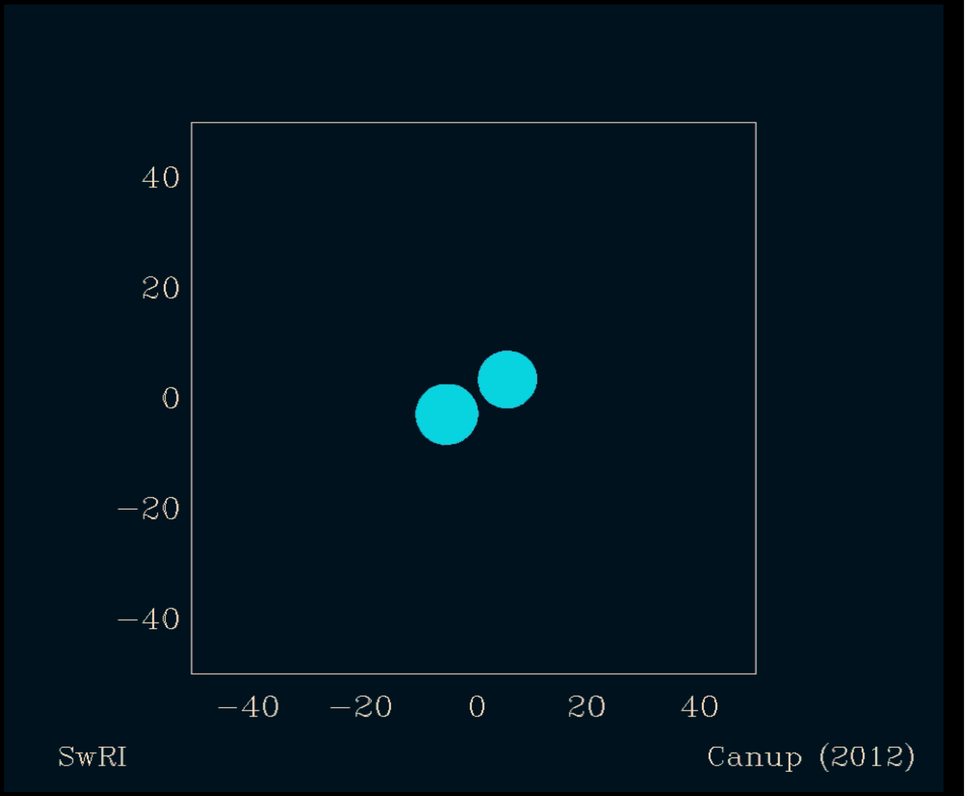
[1]Institute for the Science of Exploration Targets
Southwest Research Institute, Boulder CO, USA

Non-canonical disks

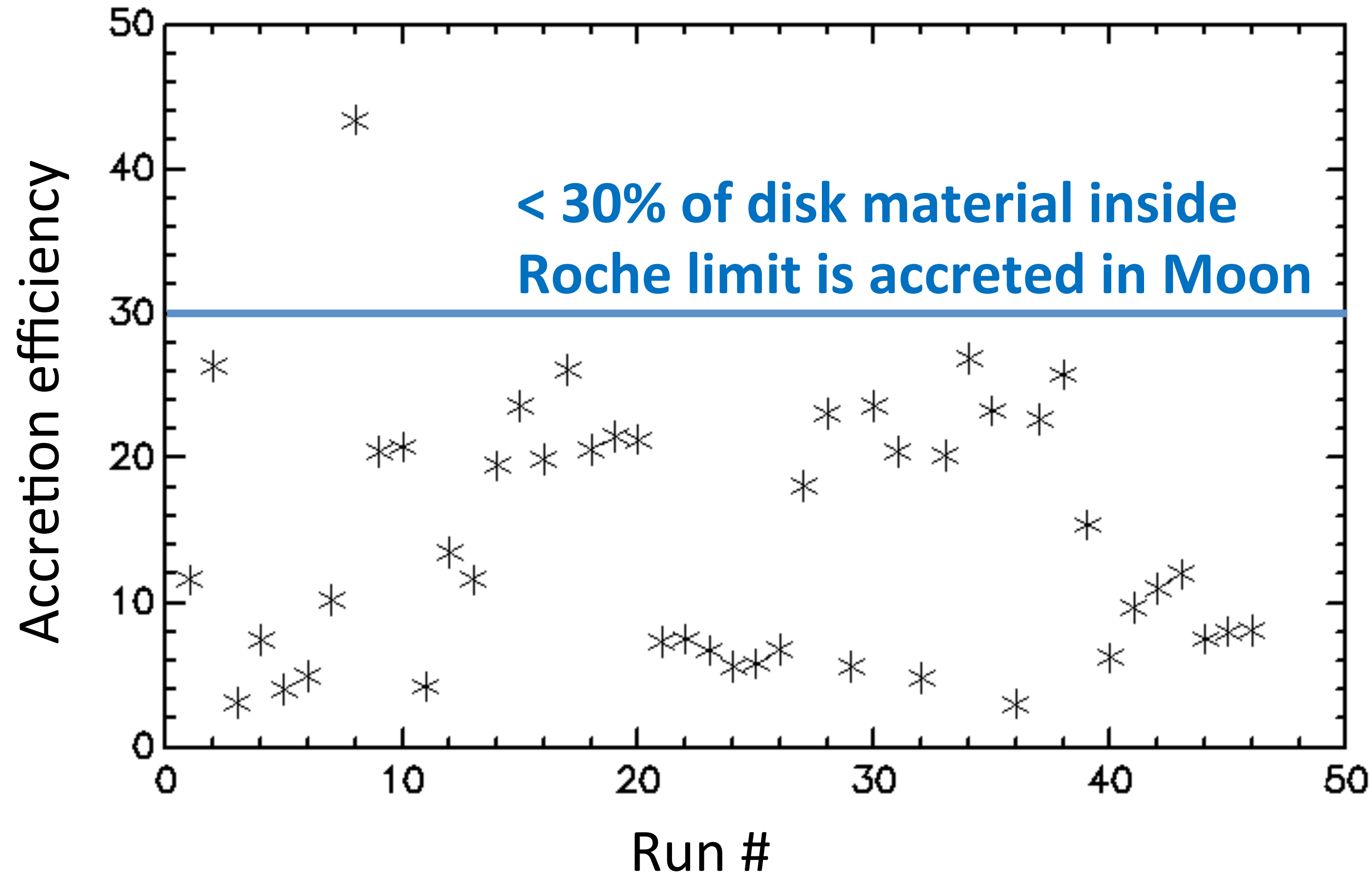
- New kinds of Moon-forming impacts:
  - Larger impactors (Canup 2012)
  - Higher impact velocities (Ćuk & Stewart 2012)
- Produce more compact disks, most mass inside Roche limit



- Disk composition close to that of post-impact Earth
  $\Longrightarrow$ explains Earth-Moon identical Oxygen isotopes

Concern #1: Poor accretion efficiency of Roche-interior material

Results for canonical disks from Salmon & Canup (2012)

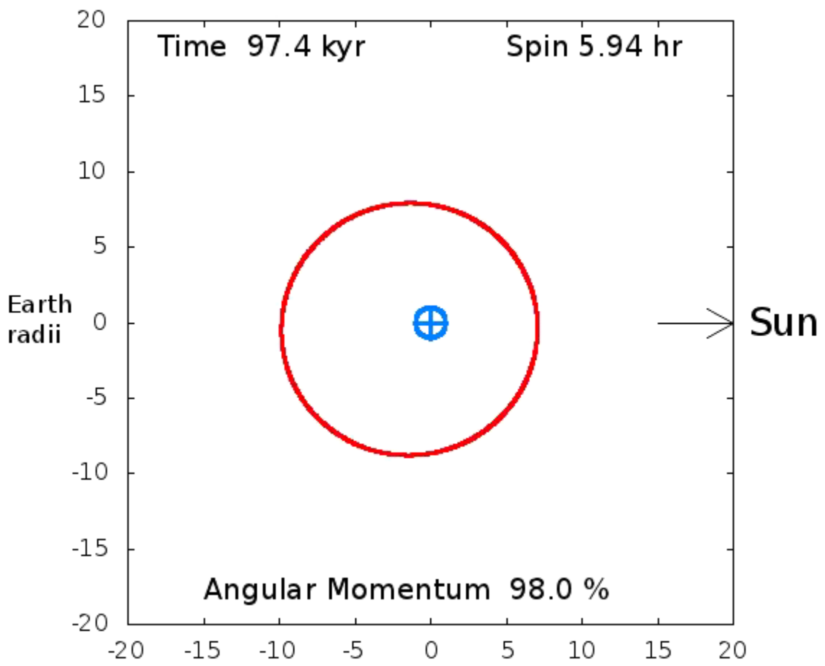


Concern #2: Evection resonance

Non-canonical impacts leave Earth with ~2.5hr rotation

$\Rightarrow$ excess angular momentum

From Ćuk & Stewart (2012)



- Evection resonance between Earth, Moon and Sun

  $\Rightarrow$ decrease Earth-Moon angular momentum by ~2 (Ćuk & Stewart 2012)

- Capture into resonance depends on Moon's initial orbital parameters (e.g. Touma & Wisdom 1998)

Question

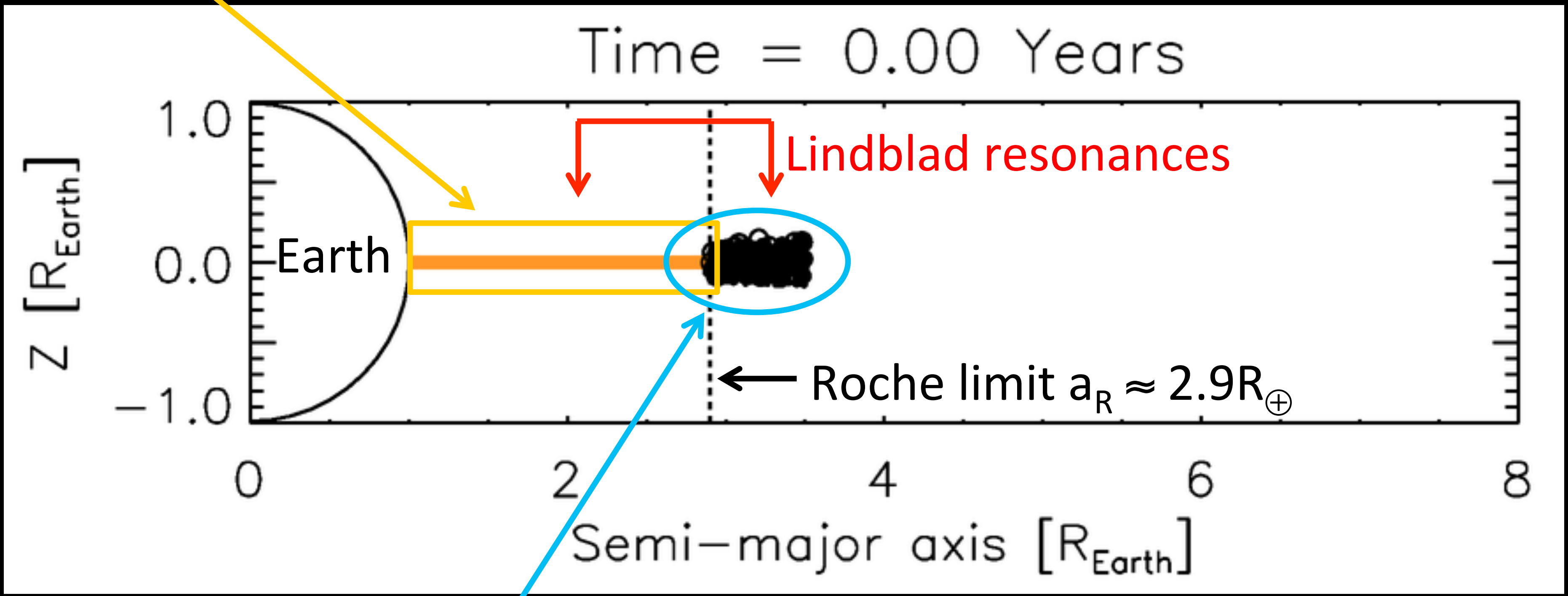
Characteristics of satellites formed from non-canonical protolunar disks ?

- Concern #1: Can we form lunar-mass objects ?
- Concern #2: Moon initial orbital parameters compatible with capture into evection resonance?

Our concept model

Salmon & Canup (2012)

within Roche limit: uniform fluid disk



beyond Roche limit : individual particles tracked with N-body code SyMBA

See also Canup & Ward (2000)

Disk evolution

- Roche-interior disk
  - Mixture of vapor & liquid, well mixed and co-evolve (Thompson & Stevenson 1988)
  - Viscous spreading
    - Viscosity limited by disk's ability to cool (TS88)
    - Disk loses mass as it spreads onto the Earth
    - As material spreads beyond Roche limit, new moonlets are added to N-Body code

- Inner disk and outer moonlets interact through strongest Lindblad resonances
  - Moonlets orbits recede away from disk
  - Inner disk confined inside Roche limit

Orbital precession

- Post-impact Earth spins at ~2.5hr
  - Earth $J_2 \sim 10^{-1} >> 10^{-3}$ today
  - Causes orbital precession of moon-forming objects
  - Separates Mean-Motion Resonances
  - Moves evection resonance outward

- Roche interior disk creates additional potential
  - Precession rate of lunar perigee ϖ:

$$\varpi \approx \Omega_M [3/2\, J_2 (R_\oplus / a_M)^2 + 2 M_{disk} / M_\oplus * f(a_M, r_{disk})]$$

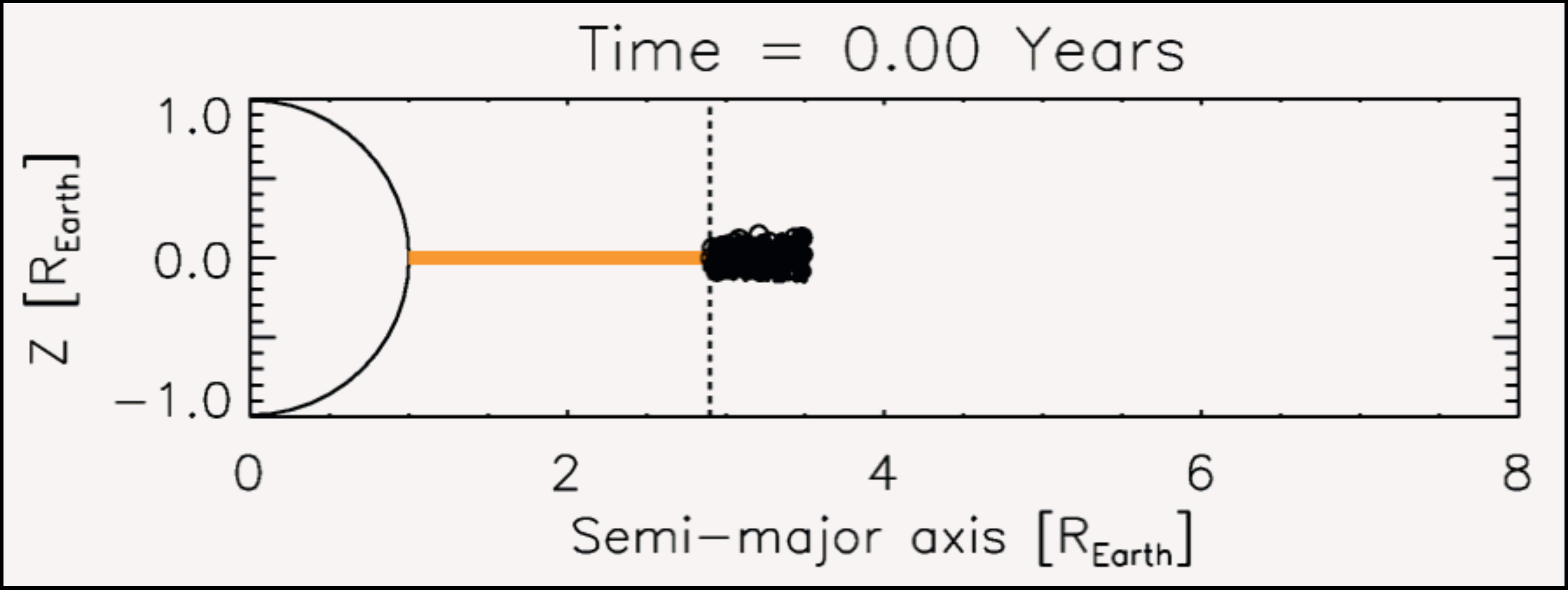
  - Similar to increasing Earth $J_2 \Rightarrow$ moves evection outward
  - As disk dissipates, evection moves inward

Simulation protocol

Based on “successful” cases of Canup (2012) and Ćuk & Stewart (2012) = disks with least deviation from post-impact Earth composition

	Non-canonical (This work)	Canonical (Salmon & Canup 2012)
Specific Angular Momentum	0.850 - 0.925	0.840 - 1.100
Disk mass	1.75 - 3.25 M_L	2.0 - 3.0 M_L
Mass fraction < a_R	66 - 90%	50 - 80%
Outer edge	3.5 - 4.5 $R_\oplus$	4 - 8 $R_\oplus$

Accretion dynamics

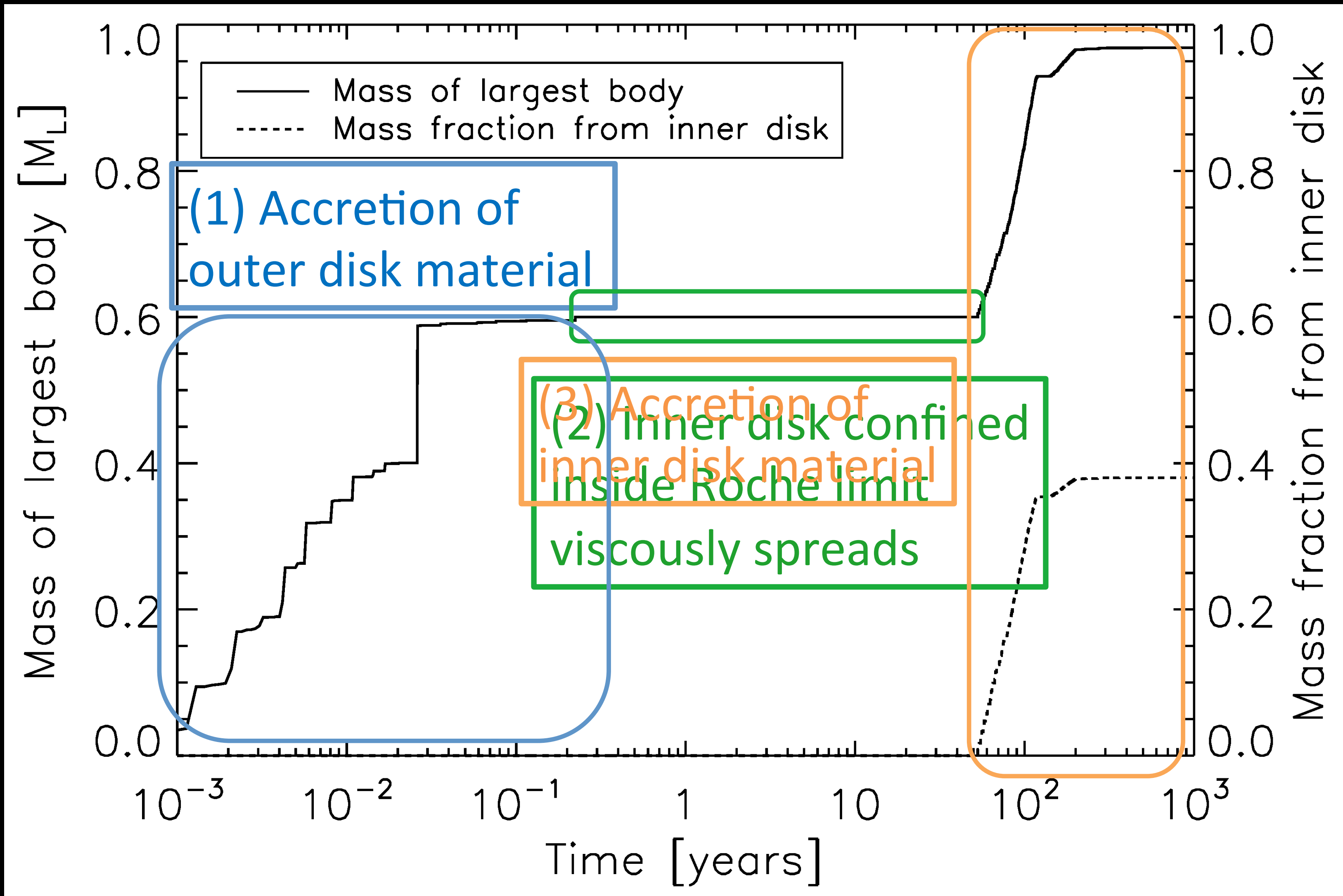


Phase 1: outer bodies accrete and confine inner disk inside Roche limit

Phase 2: inner disk slowly viscously spreads back out

Phase 3: new bodies accrete at Roche limit and continue growth of the Moon + serve as relay with inner disk causing moon orbit to expand

Accretion dynamics



3-step accretion over ~200 years ⇒ identical to canonical cases

(Salmon & Canup 2012)

Moon characteristics

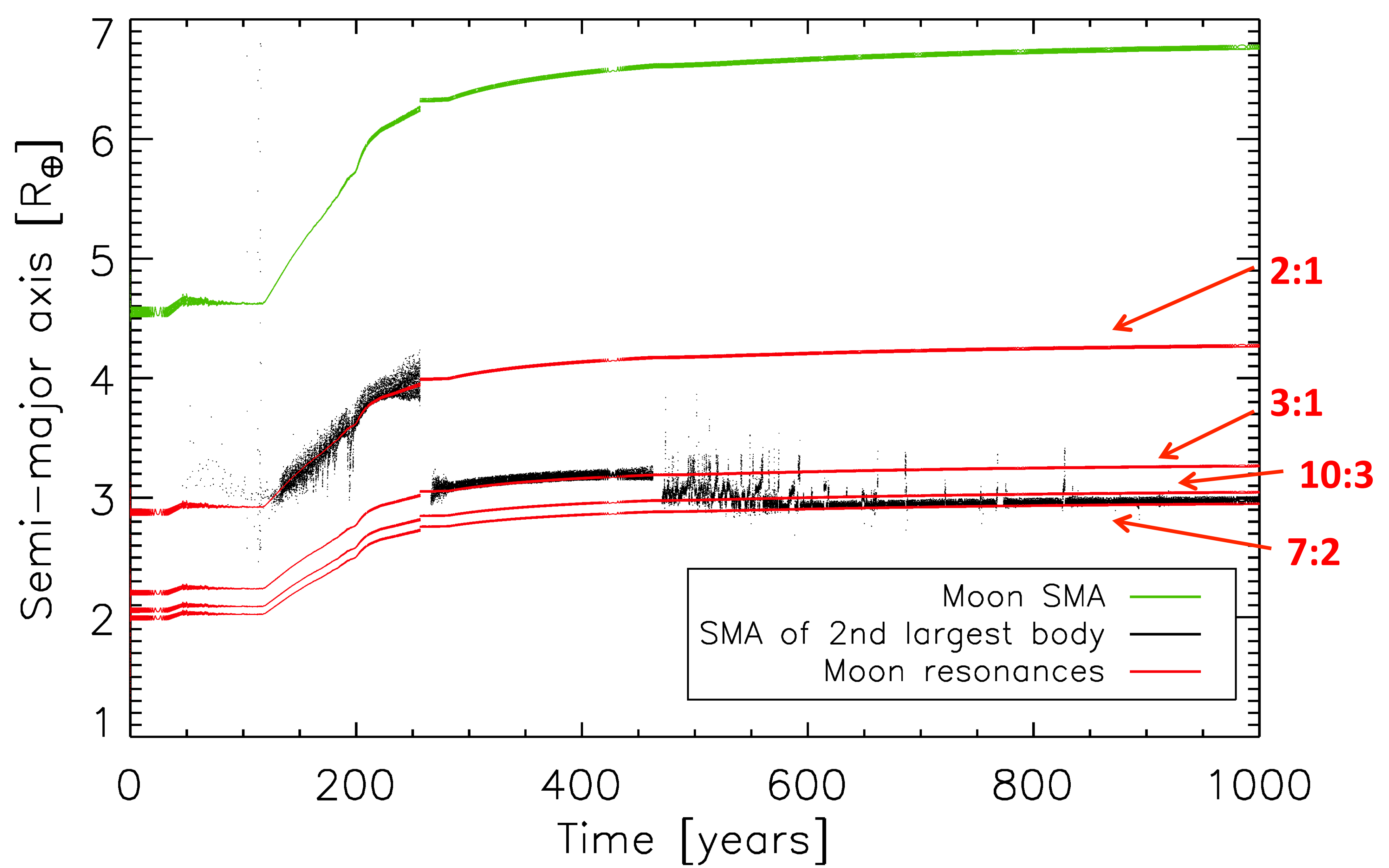
- Average moon properties at t=1000 years
  - Mass: $0.71 \pm 0.2\ M_L$ Vs. $\sim 0.8\ M_L$ in canonical disks

    $\Rightarrow$ due to low accretion efficiency of inner disk material
  - No multi-moon cases

    $\Rightarrow$ due to disk compactness
  - Semi-major axis: $8.61 \pm 2.5\ R_{\oplus}$ $\sim 6.25\ R_{\oplus}$ in canonical

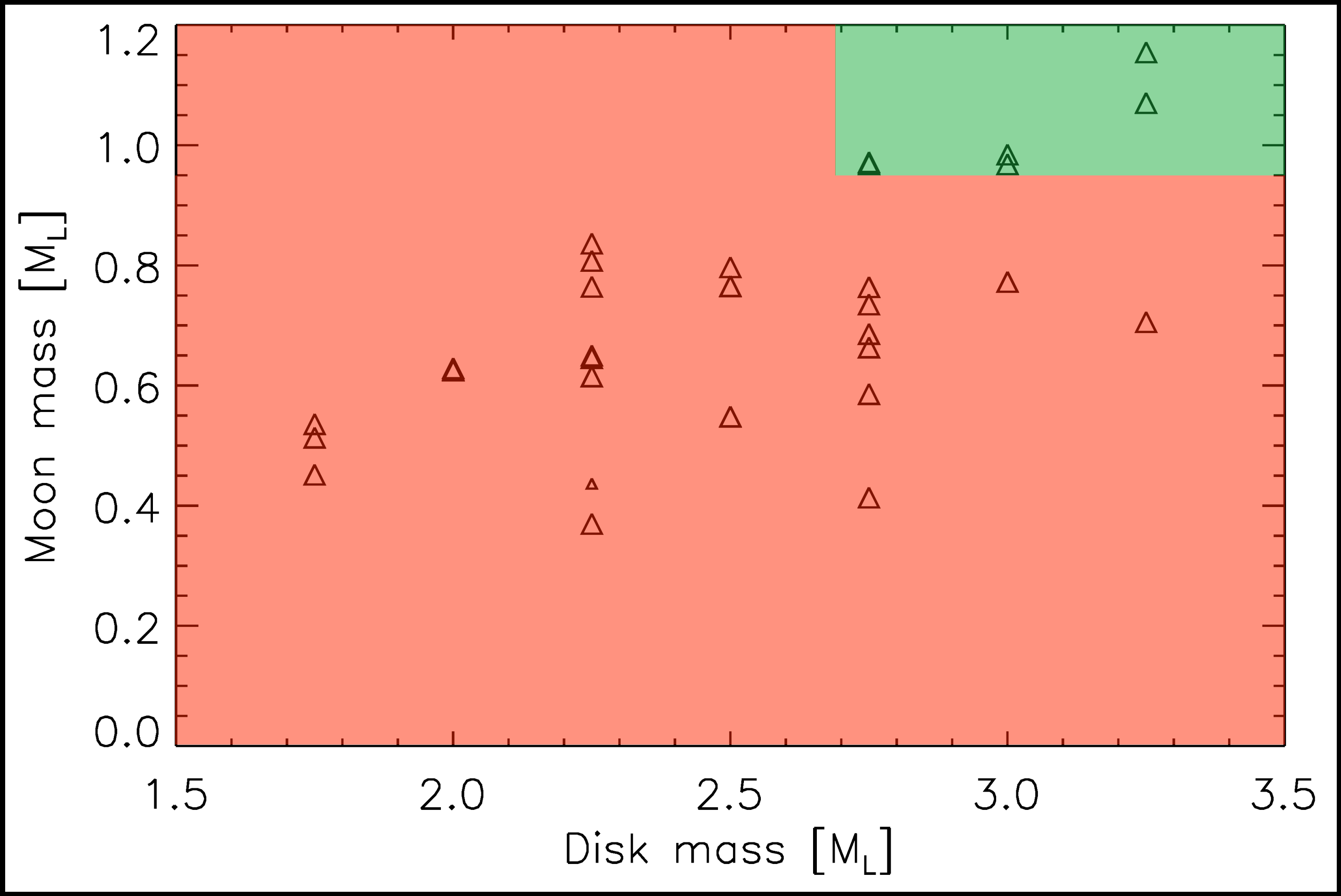
- For Moon-size objects (mass > $0.95\ M_L$)
  - 6 out of 31 runs
  - Semi-major axis: $6.65 \pm 0.2\ R_{\oplus}$ > 6.15 in canonical

Why the high Semi-Major axis?



High J_2 increases stability of capture into Mean Motion Resonances

Concern #1: Disk mass needed for $1M_L$ object

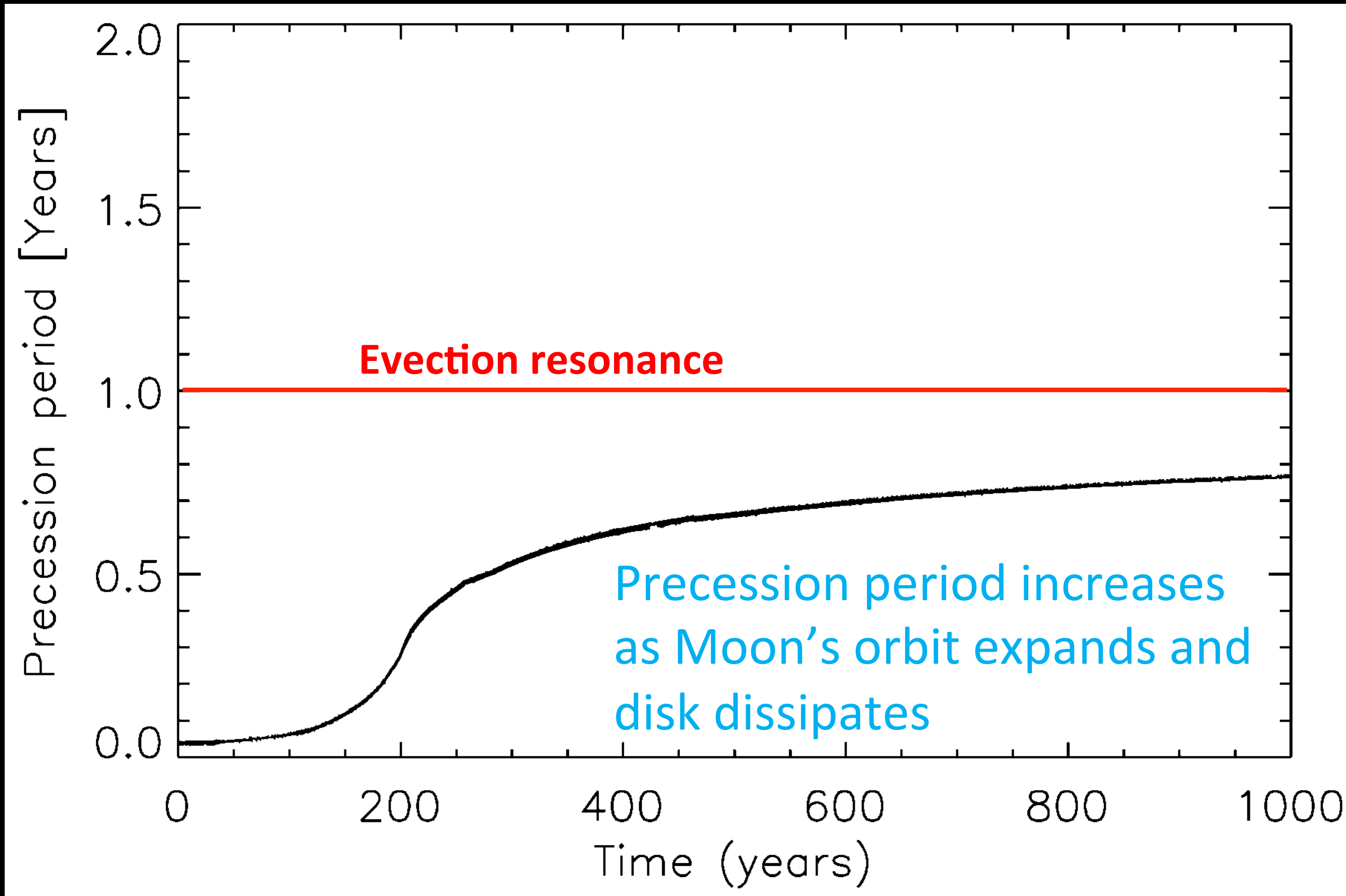


Forming a ~1 M_L object requires disk mass > $2.75M_L$

⇒ 9 out of 15 disks in Canup (2012)

⇒ 2 out of 22 disks in Ćuk & Stewart (2012)

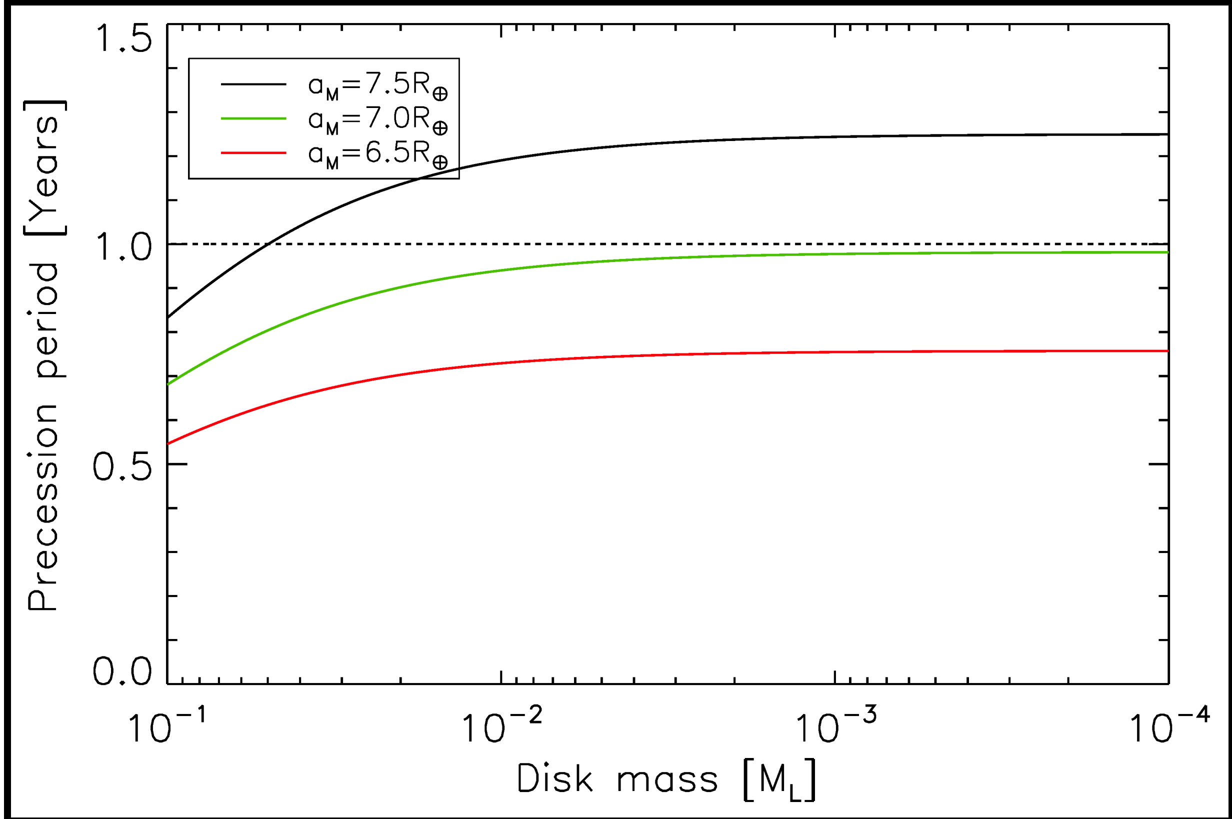
Concern #2: evection resonance



Moon still inside evection by end of its accretion

Encounter with evection

- Capture into evection resonance requires slow encounter to satisfy adiabatic criterion
- Previous studies assume Moon encounters evection due to tidal migration



However, position of evection will move inward as remaining of protolunar disk dissipates (~$10^{-2}M_L$)

Model limitations

Need to include

- Tidal dissipation in Earth

  $\Rightarrow$ excite eccentricity and semi-major axis

- Tidal dissipation in moonlets

  $\Rightarrow$ damp eccentricity and semi-major axis

These processes affect the Moon's orbital parameters and thus likelihood of capture into evection resonance

Summary

Non-canonical disks can produce a ~1 M_L object

- Moon characteristics similar to canonical cases
  - Requires disk mass > 2.75M_L
  - Moon SMA larger than in canonical cases due to more efficient capture in Mean Motion Resonances
- Encounter with evection resonance will be combination of:
  - ➢ Moon outward migration due to tides
  - ➢ Resonance moving inward as disk dissipates

  $\Rightarrow$ Need to investigate this issue closely